Unruh effect in heavy ion collisions

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ICNFP-2017, OAC, Kolymbari, Crete
17-29 August 2017

Outline

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1. Entropy
2. Unruh effect
3. Model
4. Results
5. Conclusions

Distribution: common case

X: distribution of x with probability $p(x)$

$$\sum_x p(x) = 1$$

Shannon entropy

Entropy $H(X)$:

$$H(X) = -\sum_x p(x) \ln p(x)$$

$H(X)$ defines amount of information we need to describe X = amount of information we lack about the system, thus one needs to take X into account

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Distribution: joint case

$\{X, Y\}$: distribution of x and y with probability $p(x, y)$

$$\sum_{x,y} p(x,y) = 1, \qquad p(x,y) = p(y,x)$$

$$p(x) = \sum_{y} p(x,y), \qquad \sum_{x} p(x) = 1$$

$$p(y) = \sum_{y} p(y,x), \qquad \sum_{y} p(y) = 1$$

$p(x)$ defines the probability of x irrespective to y

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Conditional distribution

Conditional probability $p(x|y)$:

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Schmidt decomposition and von Neumann entropy

Let $|\phi\rangle \in H_1 \otimes H_2$ $\quad H(|\phi\rangle) = -\mathrm{Tr}\,|\phi\rangle\langle\phi| \ln |\phi\rangle\langle\phi| = 0$

Schmidt decomposition:

$$\exists \left\{\phi_k \geq 0, |k\rangle_1 \in H_1,\ |k\rangle_2 \in H_2 : \langle k|k'\rangle = \delta_{kk'}\right\} :$$
$$|\phi\rangle = \sum_k \phi_k |k\rangle_1 |k\rangle_2$$

Partitions: $\quad \rho_{1(2)} = \mathrm{Tr}_{2(1)}|\phi\rangle\langle\phi| = \sum_k \phi_k^2 |k\rangle_{1(2)}\langle k|$

Partition entropy: $\quad H(\rho_1) = H(\rho_2) = -\sum_k \phi_k^2 \ln \phi_k^2$

Example

$$|\phi\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right) \text{ -- Bell state}$$

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Frames of reference

Inertial frame of reference (IFR) : vacuum $|\phi\rangle$

$$a|\phi\rangle = 0$$

Non-inertial frame of reference (NFR) with acceleration α: horizon thermal radiation with Unruh temperature T [Unruh, 1976]

$$T = \frac{\alpha}{2\pi}$$

Bosonic creation and annihilation operators in IFR and NFR are connected via Bogoljubov transformations:

$$a = \frac{1}{\sqrt{1 - e^{-E/T}}} b_{\rm out} - \frac{\sqrt{e^{-E/T}}}{\sqrt{1 - e^{-E/T}}} b^{\dagger}_{\rm in}$$

$$|\phi\rangle = \sqrt{\frac{1 - e^{-E/T}}{1 - e^{-NE/T}}} \sum_{n=0}^{N-1} \sqrt{e^{-nE/T}} |n\rangle_{\rm in} |n\rangle_{\rm out}$$

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Unruh effect

IFR: no horizon, pure vacuum state $|\phi\rangle$

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$$H\left(|\phi\rangle\right) = 0$$

NFR: horizon, mixed state $\rho_{\rm out}$

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Unruh effect in heavy ion collisions

Particles are being born via tunneling through the Unruh horizon [Kharzeev and Tuchin, 2005; Satz, 2007; Castorina et al, 2007]: estimation of T_{U} from string breaking mechanism gives $T_{\mathrm{U}} \approx T_{\mathrm{H}}$

Model

- Two colliding nuclei
- The born particles are described by multiplicity n and energy E joint distribution $\{n, E\}$

$$\begin{aligned} H(n, E) &= H(n) + \langle H(E|n) \rangle_n \\ &= H(E) + \langle H(n|E) \rangle_E \end{aligned}$$

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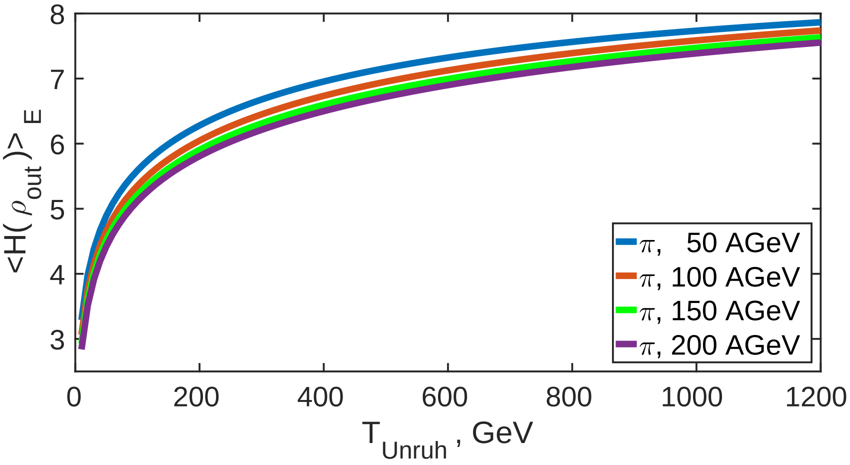
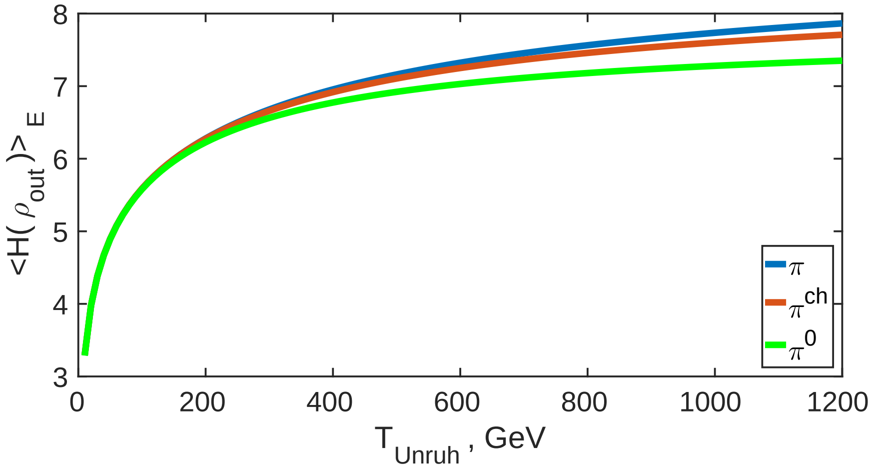
π entropy at different $\sqrt{s}$



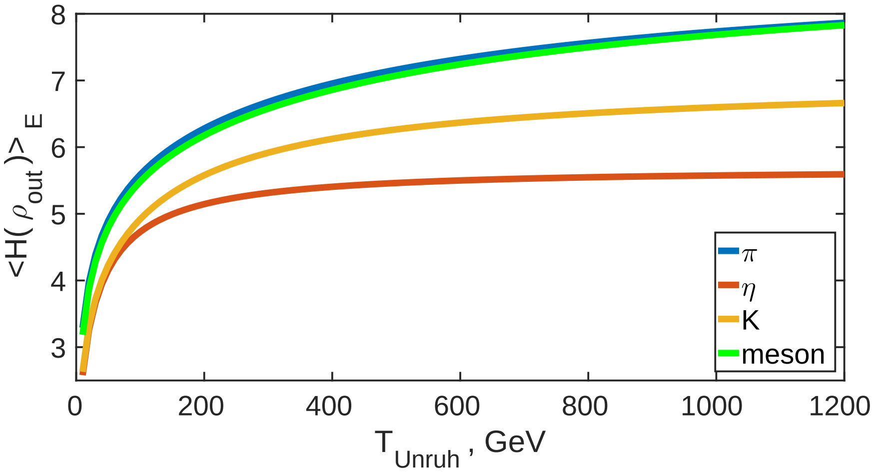
Dependence of $\langle H(\rho_{out})\rangle_E$ on T_{U} for π after freeze-out, UrQMD calculations of Au+Au collisions at different $\sqrt{s}$

π entropy: charge dependence



Dependence of $\langle H\left(\rho_{out}\right)\rangle_E$ on T_{U} for π, π^{ch}, π^0 after freeze-out, UrQMD calculations of Au+Au collisions at $\sqrt{s} = 50$ AGeV

Meson entropy: type dependence



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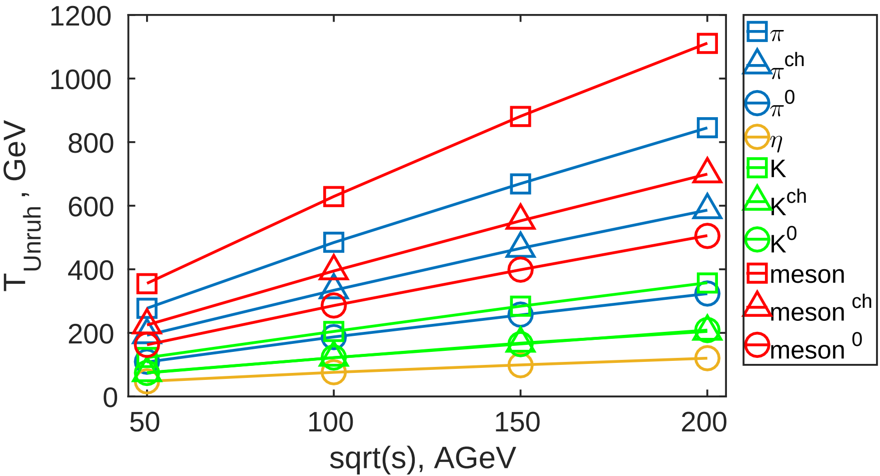
Unruh temperature T_{U}



Dependence of T_{U} on collision energy $\sqrt{s}$ and charge for π, η, K, mesons after freeze-out, UrQMD calculations of Au+Au collisions. Lines are to guide the eye

Conclusions

- $T_{\mathrm{U}} \gg T_{\mathrm{H}}$
- T_{U} increases with $\sqrt{s}$
- T_{U} is proportional to charge number (approximately only)

Discussion, open questions

- At given multiplicity and energy distributions, Unruh source with $T = T_{\mathrm{U}}$ is equivalent to the corresponding heavy ion collision
  Alternative: particles are being born completely thermal by the Unruh source with $T = T_{\mathrm{U}} \gg T_{\mathrm{H}}$
  Example: fusion process at the Sun is of MeV range, while the outgoing radiation is of eV range
- Unruh effect, due to $T_{\mathrm{U}} \gg T_{\mathrm{H}}$, may explain thermalization (see previous item) at early times by the geometry only

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- $T_{\rm U}$ strongly depends on parameter $N = \max(\{n\}) + 1$: it requires more accurate estimation
  But: with N decreasing, $T_{\rm U}$ is expected to increase sharply
- Influence of environment: $H(n, E)$ is expected to decrease for pp or ee collisions, that may result in decreasing of $T_{\rm U}$
  But: in the model applied, any particle is being born due to the Unruh effect. As a result, the influence of environment may be insignificant.
- Theoretical verification: dynamics analysis, pp and e^+e^- collision simulations
  Experimental verification: measurement of the density matrix of the born particles from their multiplicity and energy distributions

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THE END

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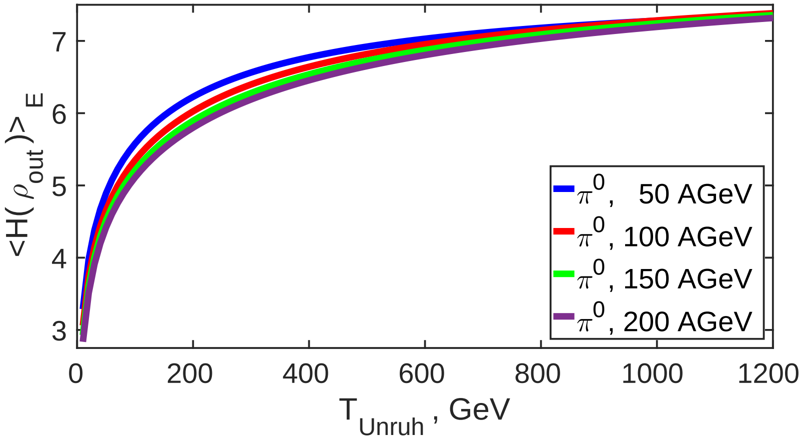
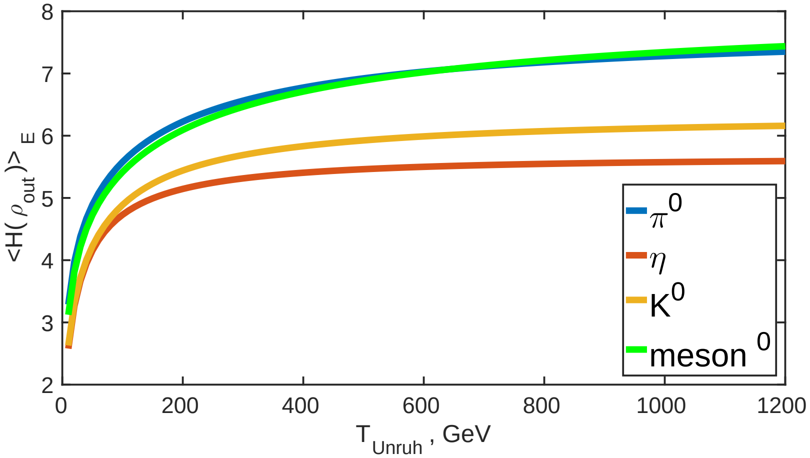


Dependence of $\langle H(\rho_{out}) \rangle_E$ on T_{U} for π^0 after freeze-out, UrQMD calculations of Au+Au collisions at different $\sqrt{s}$

Meson entropy: type dependence for neutral



Dependence of $\langle H(\rho_{out}) \rangle_E$ on T_{U} for π^0, η, K^0, meson^0 after freeze-out, UrQMD calculations of Au+Au collisions at $\sqrt{s} = 50$ AGeV